

PSYCHOPHYSIOLOGICAL EFFICIENCY OF THE MACACUS MONKEY
AFTER CORTEX ABLATION

K. Bättig and H.E. Rosvold

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K.Bättig* and H.E.Rosvold**

With 5 Illustrations

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A general survey is given over the effect of ablation of the secondary cortex in Macacus monkeys on their performance in various learning tests. For the secondary or association cortex of the monkeys there exists a distinct subdivision into function-specific areas. Total extirpation of the frontal secondary cortex results in an irreparable loss of the ability for delayed reaction. Frontal-lobe ablation led to the inability of sensory discrimination, typical hyperactivity, and disturbance of the normal emotional behavior. Application of these findings to human pathology is still impossible, because of the lack of similar tests on human subjects.

I. INTRODUCTION

Author ***/157

The old concept that the association cortex, known also as higher or secondary cortex, represents the specific organ for the highest nervous performances of learning, association, and thinking, must be considered obsolete today. Just as such functions are linked with the intactness of other cerebral

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structures, so does the secondary cortex have functions that have nothing to do with higher psychic functions.

Nevertheless, this partial aspect of the psychofunction still remains in the sphere of interest and at the focus of modern cortex research. In the past century, observations by natural scientists and physicians led to various attempts of interpreting the psychofunctional organization of the cortex, which could not be upheld in the light of later discoveries. That the more recent work of the past 30 - 50 years has cleared up many of these problems is mainly due to the fact that the refined and better developed methods of experimental psychology were finally accepted by physiology as a replacement for pure /158 observation.

Three main classes of psychic performance are the subject matter of modern psychophysiology:

1. Nonlearned reactions to environmental stimuli, which include instinctive behavior generally, spontaneous activity, tropistic behavior, etc.
2. Learned reaction to environmental stimuli. This includes all reactions that can be explained as "conditioned reflexes", i.e., reactions which have been acquired by an animal as an adaptation to a special environmental condition and which are canceled again as soon as these special environmental conditions no longer exist.
3. "Symbolic Reactions". These are reactions which are not executed as a response to an environmental stimulus but which originate in an endogenous neural stimulus of the animal. This means that the endogenous stimulus substitutes the nonexistent external stimulus, i.e., it represents a "symbolic " stimulus. In human subjects, this

group includes, for example, thoughts, concepts, speech, etc. The designations intelligence, reasoning, expectation, etc. all represent synonyms for this class of psychic events.

In searching for correlations between these three classes of psychic functions and the structure and physiological mode of function of the nervous apparatus, three methodic possibilities are basically in question:

1. The experimental release of reactions by adequate stimulation of neural structures. Until now, this particular method has been quite useful in conducting research on the first class of psychic activities. However, considerable difficulties were encountered in the attempt of using this method for establishing relations with learned or specifically with symbolic behavior.

2. The study of psychic events as a function of physiological processes in the central nervous system. This method would be the most direct, but the knowledge in normal physiological processes within the nervous system is still too little advanced. It is true that correlations of psychic processes of the first class (specifically, arousal reaction, fright reaction, alarm reaction, etc.) with electroencephalographic processes were established and that, more recently, psychic processes of the second order (conditioned reactions) were paralleled with characteristic encephalograms. However, no relations were discovered between electrical processes in the brain and psychic events of the highest, or third, order. In addition, the wide field of possible relations between biochemical reaction courses and psychic processes is still in the very beginning of systematic research.

3. The study of functional deficit after selective extirpation of components of the nervous apparatus. This method resulted in correlations between the central nervous system and all three classes of psychic behavior.

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However, such an ablation technique has various disadvantages. Not only does it damage the one carefully investigated function but also other functions as well as nonpsychic functions. This technique consists in an amputation of the nervous system whose sequels are completely or partially compensated by the organism so that an investigation after operation leads to a resultant between this compensation and the actual direct sequel of the intervention. In addition, the ablation technique frequently is based on too rigid an anatomic concept of the functional structure of the nervous apparatus, which increases the danger that, in this procedure, dynamic aspects of the cerebral function are overlooked.

Nevertheless, these ablation studies in animal experiments may be of immediate interest because of the fact that they can be directly correlated with the procedures in clinical work where surgical or pathological elimination of brain tissue involve the same problem complex. In the present paper, ablation studies on Macacus monkeys are discussed, with special emphasis on the effect of ablations on the associability and on higher psychic performances.

GENERAL METHODICS

Experimental Procedure

Most studies were based on the following plan: If a given ablation I damages the function A but not the function B whereas an ablation II does exactly the opposite, it can be assumed that the two tested cortex fields have different values. For this reason, most studies were made on several groups with an average of about four animals. Each group was given a different ablation and all animals were compared by means of the same psychological tests.

Surgical and Anatomical Methods

In general, the animals were operated under anesthetic and aseptic conditions. After termination of all psychological tests, the animals were sacrificed, the brains were removed, and the surgically produced ablations were histologically controlled. As an indication for the extent of the ablations made, the cyto-architectonic cortex chart of the *Macaca mulatta* monkey, compiled by v.Bonin and Bailey and shown in Fig.1, has been used for the discussion of the individual studies given below.

The classical numerical designations by Brodmann were also entered into these charts for the individual fields.

In some of the ablations discussed in the present report, the authors used practically the same limitations and the same scope, so that one can almost speak of "standard ablations". The four most important of these ablations are schematically shown in Fig.2. Involved were the "frontal ablation" (F), /160 the "parietal ablation" (P), the "occipital ablation" (O), and the "temporal ablation" (T). Wherever these designations are used in the following text, the anatomical concept will be based on the fields entered in Fig.2. The delimitations of these fields can be described as follows: The "frontal ablation" is restricted to the lateral area of the frontal lobe inclusive of the pole but not extending over the ventral or medial area of the lobe. Caudalward, this ablation extends to the boundary line between the Brodmann fields 4 and 6 in accordance with Fig.1. The "parietal ablation" comprises the lateral portion of the parietal lobe and is rostrally limited by the sulcus intraparietalis and caudally by the sulcus lunatus and the sulcus temporalis superior. The "occipital ablation" exists in the entire lateral portion of the field No.17 in

accordance with Fig.1. The "temporal ablation" ends about 2 cm before the pole of the temporal lobe. Caudalward, this ablation extends to Labbé's vein and

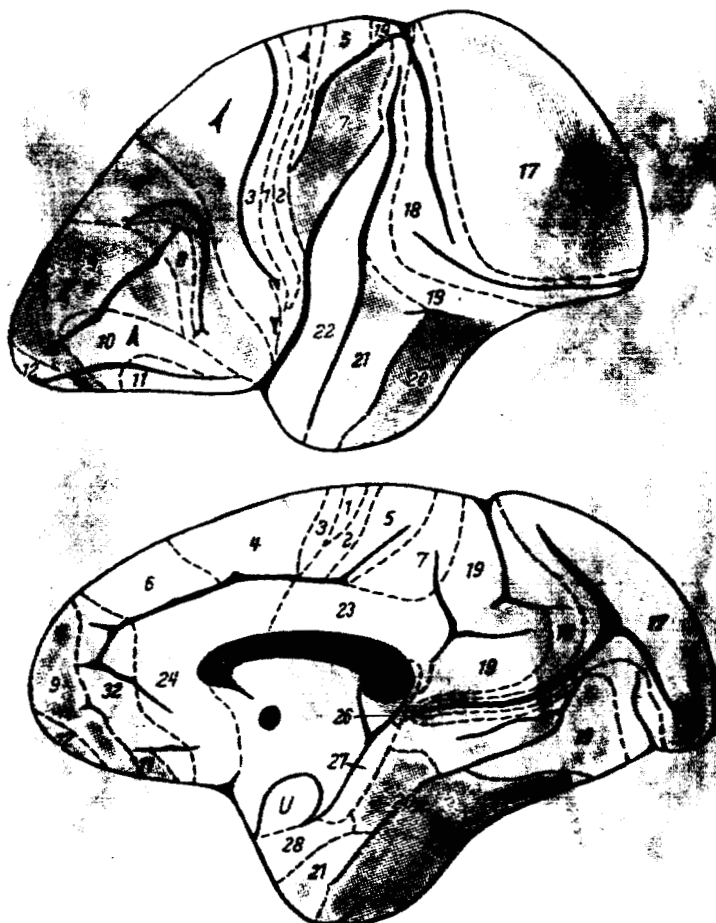


Fig.1 - Cyto-Architectonic Presentation of the Cortex of the Macaca Mulatta Monkey, According to von Bonin and Bailey (Bibl.4)

Top: Lateral view; Bottom: Medial view

dorsalward to the sulcus temporalis superior, comprising, in the ventral /161 area of the temporal lobe, the portions of the Brodmann field No.20 according to Fig.1.

Psychological Test Setup

Most authors use for their investigations the simple apparatus marketed

under the name "Wisconsin General Testing Apparatus" (WGTA) in various modifications.

The apparatus (Fig.3) consists basically of a selection chamber with feed boxes. The front and rear walls of this chamber are designed as up- and down-sliding doors. The monkey to be tested sits in his cage on one side of the chamber while the experimenter sits on the other side, where he is able to manipulate the two sliding doors by cables in such a manner that either he himself or the monkey have access to the chamber. The tester uses the chamber whenever he wishes to prepare a test situation, such as hiding food in one of the feed boxes. The animal is unable to watch the process since the sliding door is nontransparent toward his side. Conversely, when the animal has access to the chamber, the experimenter is able to observe the reaction of the animal since his own sliding door is semitransparent.

In the future, the use of fully automatic testing equipment might open new possibilities for the functional cortex research on animals. The principle of automation has been used for years in the well-known Skinner technique of the "operant condition" and has been specifically useful in experimental behavior research as well as in psychopharmacology.

Testing of Non-Learned Behavior

The WGTA is used for testing the visual acuity and the attitude of the animal toward unknown new objects which are displayed in the apparatus. Conversely, social, emotional, and sexual behavior is usually observed in free-group and individual situations and evaluated in accordance with an arbitrarily selected point system. Generally, spontaneous activity is measured in a standard housing cage, by using selenium cells for counting how often the

animal crosses a light beam within a given period of time.

Testing of Associative Learning

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In principle, the animal in the WGTA is confronted with a given situation

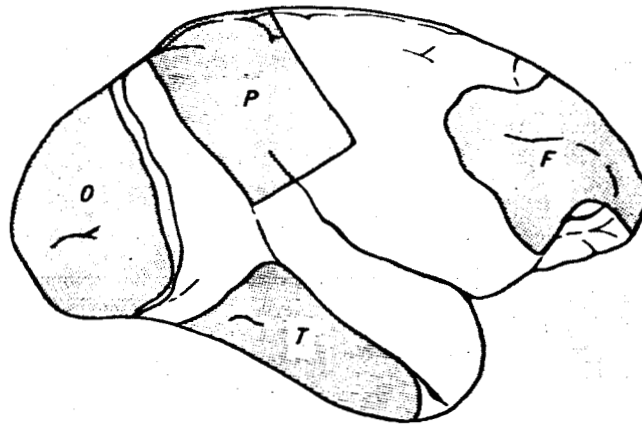


Fig.2 - Schematic Presentation of Four "Standard Lesions"

as many times as is necessary for it to learn that, when subjected to a certain stimulus, food will be found only in one but not in the other feed box. In the case of simple "simultaneous selection", the chamber of the WGTA contains at least two feed boxes or feed hoppers. One of these two boxes, alternately the left or the right-hand one, is covered by the marker under which the food is always hidden while the other marker covers no food. After a number of days, each comprising about 20 - 50 individual tests, a normal animal will have learned, depending on the degree of difficulty of discrimination, that the food must be looked for only underneath of one of the two markers. In this manner,

differentiation of visual, olfactory, and tactual characteristics can be tested.

However, auditory characteristics cannot be coordinated with one or the other of the feed boxes. In this case, the problem is solved by giving the animal one single differentiation sound per individual test and to place the food in one of the boxes for this particular sound while the food for the other

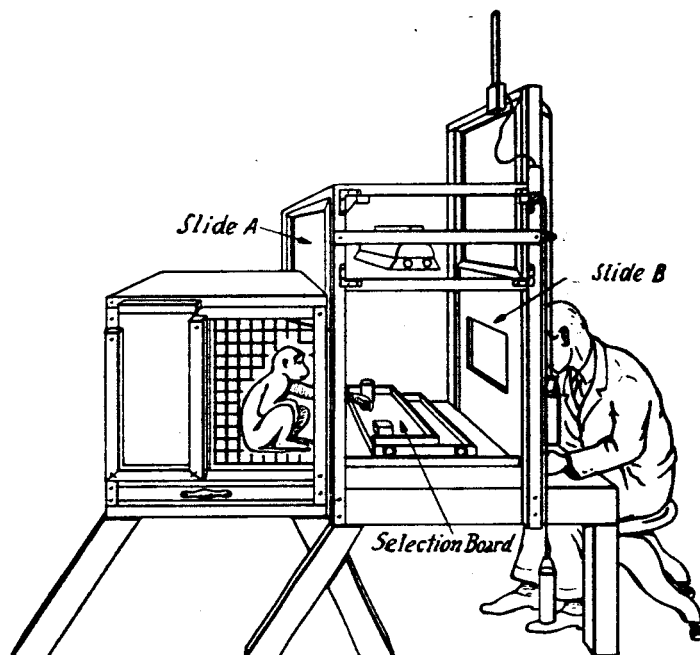


Fig.3 - "Wisconsin General Testing Apparatus" (WGTA), According to H.F.Harlow and P.H.Settlage (Bibl.33).

The slide A is nontransparent. The slide B is semitransparent and permits the observer to control the board without being seen by the animal

sound is placed into the other box. Consequently, in this type of test the two food boxes are neutral, meaning that they have no discriminative markings. Depending on the individual stimulus, the animal has to select one or the other box. This specific test variant is known as simultaneous "conditional selection" (selection according to the given condition). Naturally, visual,

olfactory, and tactual stimuli can also be taught with this method.

In the very often called "successive selection", the selection board contains only one feed box and only the stimulus A or B is given in each test. The stimulus A always means that the food is placed in the single existing feed hole. The stimulus B means that there is no food in the hole. Whereas in the so-called "simultaneous selection" the animal learns to open the proper feed box of several boxes, it must learn in the successive selection to expect or not to expect food depending on which stimulus is given, i.e., either to open or not to open the single feed box.

Apparently, in the WGTA the two types of tests have differing difficulties. In general, simultaneous selection is learned more rapidly. In addition, in the simultaneous selection it is always observed that an animal, after a preliminary time of unsuccessful questioning "where is the food?" will react suddenly in the correct sense, i.e., in the sense of a "finally" experience. In contrast to this, in successive selection the final success is obtained only after a certain period of time; the animal learns gradually not to react to an unrewarded stimulus.

Testing of Symbolic Reactions

For this group of psychic performances, the WGTA is the apparatus most commonly in use.

Delayed Reaction: In principle, a time delay is inserted between the stimulus for reaction and the reaction itself. In practical work this is done by lifting the two shields of the WGTA while the food is placed into one of the two feed holes. Thus, the monkey is able to see at which place the food is being hidden. Then, the shield is lowered in front of the animal and both feed-

ing holes are covered with neutral cardboard covers. Only seconds or minutes later will the experimenter lift the shield in front of the animal. This means, the animal must bridge the time of delay by a neural "symbolic process" because of the fact that the physical stimulus is no longer present at the instant of reaction. The duration of the delay and the type of test for this problem can be varied at will. For example, the problem can be given "directly" by showing the reward to the animal before the delay or "indirectly" by showing the animal a corresponding symbol for the food above the correct feed hole, instead of the food itself. In addition, the test can be conducted in accordance with the principle of "simultaneous selection" or with the principle of "successive selection". In the first case, the animal selects either the left or right-hand feeding place after the delay. In the second case, depending on the preceding stimulus, the animal will reach for the hiding place or will not react at all. By means of such variants, it is possible to vary the degree of difficulty for the animal.

Delayed Alternation: In this delayed test, no stimulus is offered to the animal before the delay. Instead, the reward is alternately placed into the left or the right feeding hole. Consequently, the monkey must learn to use the result of the preceding experiment as stimulus for each reaction. This problem can also be posed in variants resembling those used in the delayed reaction.

Testing of "Hypotheses" of the Animal: A difficult or unsolvable /164
problem is given the animal. Each reaction is recorded and equal reactions are compiled into groups. If the animal exhibits a series of reactions Type A, these experiments represent the first "hypotheses" or "expectation" of the animal; a second succeeding group of reactions of Type B represents the "second hypothesis" of the animal, etc. If the animal has no "hypotheses", its at-

tempts at solution will be unsystematic, accidental, and not determined by an active central process of "reasoning".

Series Learning: In these tests, the animal is given a number of successive discrimination problems (visual or other problems). Normally, each of the individual problems is given the animal only in a definite number of individual tests, for example each problem in only ten individual tests with a new problem for each day. In these few individual tests, a given animal will be unable at the beginning of the test to solve an individual problem. However, the further the test proceeds the less errors will the animal commit per each new problem. As an explanation, it must be assumed that the animal attacks the new problems by making use of previous experiences or of previously committed errors. Speaking figuratively, it is possible to see how a monkey will "learn to learn" in how far he can "abstract" from earlier situations to new situations. To prove that this performance is of a higher "symbolic" or "complex" nature, a phylogenetic explanation may be more suitable than theoretical considerations. Fish are unable to perform in this manner and rats only to a limited extent. Lower monkeys and cats show remarkable "abstraction performances" and chimpanzee finally perform with "monkey-like agility" while human subjects exhibit maximum performance in this field. Similar statements are valid for the other above-mentioned symbolic processes.

II. LEARNING OF VISUAL ASSOCIATIONS

In 1936, Klüver and Bucy (Bibl.45) mentioned that the consequence of extirpation of the temporal lobe in Macacus monkeys produced - in addition to an increased oral and general exploration tendency, reduced emotional excitability, and hypersexuality - also cases of so-called "psychic blindness". Because of the finding of "psychic or soul blindness", further research was con-

fronted with the following questions: Does a critical focal field for higher visual functions, which is locally delimitable from other fields responsible for the remaining part of the symptom complex mentioned by Klüver and Bucy, exist within the temporal lobe of the Macacus monkey? Outside of the temporal lobe, are there no other secondary cortex fields connected with higher associative visual functions? How can the behavior deficit circumscribed by "psychic blindness", be experimentally more accurately characterized? In addition /165 to the visual psychic function, are no other higher psychic functions involved after ablation of the temporal lobe? What functional relations exist between the visual fields of the temporal lobe in question and the primary optical system? A better understanding of these problems was obtained by a number of investigations of later years.

Focal Field of Visual Learning Function in the Temporal Lobe

Pribram and Bagshaw (Bibl.88) made systematic investigations on monkeys after partial ablation of the temporal lobe, to determine the symptom complex described by Klüver and Bucy. The authors found that, after extirpation of the frontotemporal complex (gyrus orbitalis posterior, anterior insular and periamygdal cortex), no deficit in the faculty of vision or in visual acuity occurred. These animals were also able to learn visual associations just like normal animals; they were also able to recognize tactual stimuli and their spontaneous activity remain unchanged. Conversely, these animals showed changes in their basal metabolism. In addition, they ate food to which quinine had been added without visible reluctance and were quite indifferent to aversive or social stimuli. On the other hand, an ablation of the lateral temporal cortex (Area 20,21,22, of Fig.2) led selectively to a greatly decelerated

learning of visual associations. This proves a functional differentiation of the temporal lobe, making it possible to correlate the temporal lateral secondary neocortex with the ability to learn visual associations, whereas the remaining portion of the symptom complex described by Klüver and Bucy is caused by ablation of the allocortex and of the juxtaallocortex of the temporal lobe. Later, Mishkin and Pribram (Bibl.64) further subdivided the portion of the temporal isocortex which is critical for the visual function. They extirpated the entire temporal lobe in two baboons, while they extirpated the superior lateral portion of the temporal isocortex in two other animals, and the ventrolateral isocortical cortex area, including the hippocampus, in the four remaining animals of the test series. It was found that the lobectomized animals as well as the animals with ventrolateral resection of the cortex learned visual associations much more slowly than animals in which the superior temporal neocortex had been removed. Mishkin (Bibl.65) made a further constriction of this critical ventrolateral cortex. In three macaques, he extirpated the ventrolateral cortex of the temporal lobe, under strict avoidance of the deeper structures of the cerebral lobe. In three animals, he resected the deeper hippocampus formation by an incision. In two control animals, he only made the incision which was necessary in the second group of animals to remove the hippocampus /166 formation. The author encountered the full picture of visual learning deficit only in animals with ventrolateral cortex ablation but not in monkeys with hippocampus resection. This series of studies thus indicates that, within the temporal lobe, there actually exists a circumscribed field which is of essential importance for the acquisition of visual associations. Figure 4, which had been prepared on the basis of a presentation by Pribram and Mishkin (Bibl.91) gives a general view over the scope of this focal region. In addi-

tion to a reconstruction of the ablation, the illustration also contains a cross section through the ablation itself and through the region of retrograde

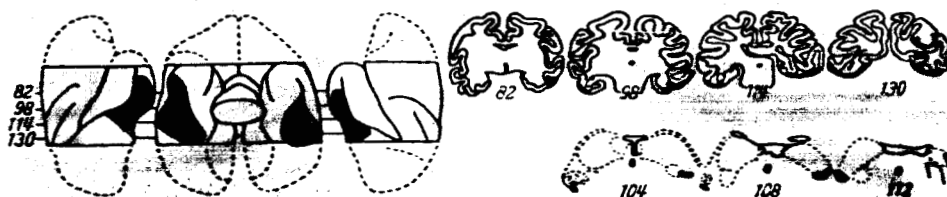


Fig.4 Focal Region for Visual Learning Performances in the Temporal Lobe, according to Pribram and Mishkin (Bibl.91)

degeneration in the thalamus. As shown in this illustration, the scope of this focal region for the acquisition of visual associations is identical with the "standard" temporal ablation presented in Fig.2. In addition to these studies, investigations by other authors such as Chow (Bibl.13), Wilson (Bibl.122), Pribram and Barry (Bibl.85) and Pasik et al (Bibl.83) led to the same result independently of one another.

Secondary Cortex Outside the Temporal Lobe and Associative Visual Functions

In a large number of individual studies the visual learning ability of macaques, after extirpation of the secondary cortex outside the temporal lobe, was investigated. All these investigations agreed in that no visual deficit learning resulted from such ablations. Of the various reports within this group only those by Blum et al (Bibl.6), Jacobsen (Bibl.39), and Lashley (Bibl.47) will be mentioned. It must, however, be added that all these authors tested the visual learning ability of monkeys, based on the principle of simultaneous selection. The results of various investigations with visual series learning or with successive discriminatory selections gave quite divergent results. Since such contradictory results occurred only after ablation of the frontal association cortex, these particular studies will be further discussed

below in the description of the functions of the frontal cortex.

Nonvisual Learning Performances and Temporal Cortex

The above-mentioned investigations by Pribram and Bagshaw (Bibl.88), Mishkin and Pribram (Bibl.64), and Mishkin (Bibl.65) concerned also the learning ability of their operated animals for the delayed reaction. None of /167 the authors, in the temporal-operated macaques, encountered a learning deficit for delayed reactions. Many other reports gave the same conclusions, namely that the ability of delayed reaction is not impaired by an ablation of the temporal cortex. Further, Pasik et al (Bibl.83), Wilson (Bibl.122), and Pribram and Barry (Bibl.85) proved that an ablation of the temporal cortex does not impair the differentiation of various tactual stimuli. Weiskrantz and Mishkin (Bibl.120) also proved that temporal-operated monkeys do not lose their ability to learn to differentiate auditory stimuli. Much less clear were the results whenever animals were tested as to their ability to discriminate between gustatory or olfactory stimuli after ablations in the region in the temporal lobe. These results will be discussed later in their pertaining correlation.

Type and Extent of the Visual Learning Deficit after Lesions of the Temporal Lobe

Various reports indicated that an extirpation of the inferotemporal neocortex resulted in a more or less extensive learning deficit, depending on the conditions under which the animals were tested.

Chow (Bibl.14) centered a study on the question as to whether the behavior deficit of temporal-operated animals disappears some time after the operation and whether the quantitative extent of the visual experience^{would influence} the extent of the behavior deficit during recuperation from the operation. His five monkeys

were given temporal cortex ablations after they had learned visual problems. Their memory for these associations was measured, in some of the monkeys, 12 days after the operation and in other monkeys only 3 months after the operation. These recuperation periods were spent by some of the animals in a normal environment, and by others in complete darkness. The observational data of this work yielded indications that a minor repetition of lost associations would occur spontaneously as a function of the duration of the recuperation time and that such a recuperation would not occur if the reconvalence were spent in complete darkness. However, the material of the work is too incomplete and the results are not sufficiently clear to accept the finding as a statistically substantiated and generally valid statement.

Riopelle and Churukian (Bibl.96) proved that a temporal cortex ablation will not simply cause a memory loss. Their operated monkeys did not learn less rapidly whenever the individual tests of a learning series were far apart in time than when the individual tests were made at closer intervals.

Chow and Orbach (Bibl.17) as well as Orbach and Fantz (Bibl.80) found that visual association will not be lost after extirpation of the temporal neocortex if this association had been "overtrained" before the operation. In their above-cited work, Mishkin and Pribram (Bibl.64) found that the learning deficit of operated animals was greater for the new learning of a given problem /168 than for the re-learning of a previously learned task. In addition, both authors found that the learning deficit was stronger and more distinct the more difficult a visual discrimination had been in itself. This finding is constant in the investigations by all authors who had tested temporal-operated monkeys as to their visual learning ability. For example, Chow (Bibl.15) found that the discrimination of many visual patterns in the serial learning tests became

completely lost after the operation, whereas the discriminations of a large number of three-dimensional objects, which also had been learned in the serial learning test before the operation, were only partially lost after the operative intervention and were relatively rapidly relearned in contrast to the more difficult pattern - discrimination test. It is here that the degree of difficulty in the differentiability of the various discriminants must be sought. Monkeys are able to learn much more rapidly to differentiate objects or colors than black-and-white patterns. Mishkin and Hall (Bibl.66) trained monkeys to differentiate size differences. They found that the operated animals were less able to obtain a learning success the smaller the size difference of the discriminants. Riopelle and Ades (Bibl.95) obtained an analogous result. In another investigation, Pribram and Mishkin (Bibl.91) varied the degree of difficulty not as a function of the differentiability of the discriminants but made the animals learn to discriminate one and the same object in a simple or in a very difficult manner. In the first test, they used the simple "simultaneous selection" for the discrimination between a tobacco canister and a pipe. The two objects were placed directly on the feed boxes; the reward was always placed underneath the pipe which latter was once placed on the left-hand and then on the right-hand feed box. In a second test, they used the "successive selection." In this test, the pipe was placed on the single feed box of the WGTA, with the reward hidden in the box, or else the tobacco canister was placed on this box without a reward. Consequently, the animal had to learn to open the box only if the pipe was on top of it. In a third test which was run according to the scheme of "conditional selection", again only one of the two objects was placed at the center of the selection board but two feed boxes were used, one to the left and one to the right of the object to be selected. If

the canister was placed at the center, the reward was found only in the right-hand box whereas if the pipe was at the center, the reward could be found only in the left-hand feed box. The unoperated animals learned this first condition within about one day, the second condition in about three days, and the last condition in about 16 days of 30 individual tests each. The temporal-operated animals required about twice as many tests to learn the first, i.e., the easiest, test variation. For the two more difficult variations, however, they needed about 3 - 6 times as many tests as the unoperated control animals before they had learned their lesson. This result is quite /169 interesting since it states that operated animals will fail not only in the case in which the visual difference between two objects or patterns to be selected is too slight but especially in the case in which the correlation between an arbitrary discriminant and the food was more difficult to recognize. The behavior deficit of the animals, consequently, is less of the "perceptive" than of the "integrative" type. The same conclusion can be drawn from the work done by Chow and Orbach (Bibl.17). In their experiments, the perception of the stimuli was made difficult by projecting the stimuli only over a short period of 20 msec to 1 sec onto the feed boxes. Discrimination of these short-time projected stimuli was learned before the operation and subsequently overtrained. After the operation, the animals were able to differentiate the stimuli despite the fact that they had been visible for such a short time only. As mentioned above, the fact that the stimuli could be at all discriminated by sensory means must be attributed to the overtraining. Accordingly, for perceptive and integrative functions the cortex of the monkey is functionally differentiated, as can be concluded also from a comparison of earlier investigations. For example, Harlow (Bibl.31) found, scotomata after a subtotal extirpation of

the cortex striatus (Field 17 in Fig.2) in the Macacus monkey while Spence and Fulton (Bibl.106) encountered a reduced visual acuity; Klüver (Bibl.44) and Settlage (Bibl.105), on the other hand, discovered no reduced visual learning ability after similar ablations. Wilson and Mishkin (Bibl.123) made it their object to obtain a direct comparison of the effect of ablations of the area striata and of the temporal neocortex on perceptive visual performances as well as on integrative visual performances. The authors extirpated the inferotemporal cortex in three monkeys and, in three other monkeys, the entire lateral surface of the area striata without its medial portion, using three additional animals as unoperated controls. According to Talbot and Marshall (Bibl.110), the lateral portion of the area striata in the monkey receives the projections of about 9° of the central field of vision. Wilson and Mishkin tested all animals as to their visual acuity, food recognition, field of view, correct recognition of crossed threads by which food could be pulled over to the animal, learning of correctly pulling such threads if they were crossed several times, learning to discriminate between objects and patterns, and finally the ability for relearning new definitions of already learned patterns. In animals in which the lateral portion of the area striata had been removed, it was found that they, in contrast to temporal-operated animals, had much more difficulty in discriminating between a larger and a smaller object (which they had learned before the operation) whenever the size difference between the two objects was reduced. In addition, their ability to recognize which of the two threads carried the food was much less than that of the temporal-operated animals, /170 as soon as these threads were crossed. On the other hand, the temporal-operated animals had much more difficulty to learn the significance of different objects or to recognize the significance of different visual pat-

terns. This result, however, must be extended by the important fact that the unoperated animals, in each of these four tests, were still better than either of the two operated groups. This seems to indicate that an ablation of the cortex striatus does not exclusively but only preponderantly influence perceptive performances and that, similarly, ablations of the temporal cortex primarily affect the integrative performances. The qualification "predominantly" places the results in contrast to earlier (above-mentioned) investigations which seemed to indicate that the cortex striatus has only a perceptory and the temporal cortex only an integrative visual function. The results obtained by Wilson and Mishkin conversely, seemed to indicate that the two neural substrata are closely interdependent and that their functional tasks complement each other within the scope of a limited specialization.

Consequently, the entity of the investigations on the degree and extent of the visual learning deficit, after lesions of the temporal cortex, justifies a number of conclusions: "the inferotemporal cortex in the Macacus monkey has a critical influence on the acquisition of a new associative performance". The more such an association had been emphasized during the training period or had even been "overtrained" the more does such a performance become independent of the intactness of the inferotemporal cortex. "If a new association can be learned readily it can also be acquired without the presence of the temporal cortex, but only at a greater effort than that needed by a normal animal." This means that other cerebral structures can substitute for the specific inferotemporal cortex, but it has never been defined which of these structures are in question here. Despite the fact that the function of the inferotemporal cortex is obviously more of an integrative nature whereas the function of the cortex striatus is more of a perceptive nature, such a functional separation

cannot be considered as being absolute. Rather, functional interactions exist between these two regions.

Functional Relations between Temporal Cortex and Primary Visual System

Authors who had resected the temporal cortex in Macacus monkeys were in agreement on the existence of retrograde degenerations in the pulvinar. This correlation between pulvinar and temporal cortex can be demonstrated also by electrophysiological methods, as demonstrated by Jasper et al (Bibl.41) and by Niemer et al (Bibl.78). Therefore, it seemed logical to investigate whether the destruction of this thalamus nucleus might have a similar effect as the resection of the temporal cortex itself. Chow (Bibl.16) used this particular procedure but was unable to demonstrate a visual learning loss after /171 electrocoagulation of the pulvinar. Whitlock and Nauta (Bibl.121) mentioned correlations between the temporal neocortex and the colliculi superiores which, in this connection, might be of some importance. However, Rosvold et al (Bibl.99), after electrocoagulation of this nuclear region, found no visual learning deficit in monkeys. Ettlinger (Bibl.22) made a thorough investigation of the alternative remaining after these negative results, namely as to whether the functionally important afferentia can be conveyed to the temporal cortex from the primary visual pathway (from the corpora geniculata laterali to the cortex striatus) or from the primary visual cortex (cortex striatus). The fact that there exist transfer connections through the corpus callosum between the two corpora striati but not between the two visual pathways was used by Ettlinger for a skilled combinatory game with serial partial ablations. Primarily, the author demonstrated that a unilateral resection of the left tractus opticus (directly behind the chiasma opticum) does not lead to the loss of an

earlier acquired association, not even if such an intervention is accompanied or followed by a resection of the corpus callosum or by a resection of the same-side left temporal cortex. In all three cases, the right-hand temporal neocortex remained intact and was able to obtain afferentia either from the primary same-side visual cortex or from the same-side tractus opticus. That a single intact temporal lobe is sufficient for visual learning had been demonstrated earlier by Mishkin and Pribram (Bibl.64). If, conversely, after section of the left visual pathway the right-hand, i.e., the opposite-side temporal cortex, is removed a considerable loss of association will result. This means that each temporal lobe obtains its visual afferentia predominantly from structures of the brain-half on the same side, either from the visual pathway or from the visual cortex. After cutting of the left tract and resection of the right temporal cortex, the left temporal cortex remains which then can obtain its afferentia only from the opposite right-hand cortex striatus. To prove such a functional afference, Ettlinger destroyed the remaining left temporal cortex or dissected the corpus callosum in a subsequent intervention. In addition to the already existing severe associative deficit, this resulted in a further drastic step-up of the deficit. This definitely indicates that functional afferentia reach the temporal cortex from the primary cortex striatus. An investigation by Mishkin (Bibl.70), who used the method of serial ablations in a similar manner, leads to the same conclusion, namely that functional afferentia must reach the temporal cortex from the primary visual cortex. It has never been definitely decided whether this takes place over a direct transcortical connection or over subcortical association pathways. Chow (Bibl.13) and also Lashley (Bibl.47), however, after resection of the area praestriata (Areas 18 and 19 of Fig.2) located between the temporal cortex and

the primary visual cortex, discovered no loss of learned associations which /172 would have indicated a direct transcortical connection between the two regions of the cortex. However, it is possible that the ablations of the area praestriata, made by these two authors, were not sufficiently complete. Another group of authors studied the function of the corpus callosum for visual associations. In their technique, they dissected the chiasma opticum in the mediosagittal plane in their experimental animals, and then covered one eye of the animal in order to make it learn with one eye only. Subsequently, tests were made to see whether the animal could understand the task also with the other eye which had been covered during the learning test. Myers (Bibl.73,74) found in this manner that an association acquired into one brain half through isolated afference was directly transmitted to the other brain half if the corpus callosum remained intact but not when the latter had been dissected. In addition, Myers (Bibl.75) showed that the posterior 25% of the corpus callosum are sufficient for the transference of a learned association from one brain-half into the other. Sperry et al (Bibl.108) even demonstrated that, after dissection of both chiasma and corpus callosum, the two brain-halves are able to acquire different visual associations, quite independently of each other. Despite the fact that these investigations on the function of the corpus callosum were not made on monkeys but rather on cats as experimental animals, they do represent an interesting supplement to the findings on Macacus monkeys. With respect to the question as to the true "mechanics of integration" of visual stimuli within the cortex, the modern "Köhler field theory" follows the old Pavlov hypotheses like a red tape. Pavlov was of the opinion that a stimulus, originating from one point, "radiated" over the entire cortex and then "concentrated" on one critical point. Köhler and Held (Bibl.46) showed directly that

slow potential variations on the cortex run parallel to the motion of a stimulus which is passed across the field of view of the animal. However, neither Lashley et al (Bibl.48) who inserted gold platelets all over the cortex, nor Sperry et al (Bibl.107) who used tantalum platelets applied in the same manner or else Thomas and Stewart (Bibl.111) who applied direct current through the cortex in one or the other direction, were able to produce any detrimental effects on the visual behavior and visual associations. This again makes questionable the old theory, repeatedly postulated in various forms, as to the mechanism of build-up of associations in the cortex.

The investigations discussed in this Chapter show that both brain halves collaborate in the build-up of associations, despite the fact that each hemisphere is able to learn visual correlations by itself. In addition, it is highly probable that each temporal cortex obtains its informations preferentially from the primary visual cortex on the same side and, to a lesser extent, from the visual cortex on the opposite side and that the exchange between the two hemispheres is taken over by the posterior quarter of the corpus callosum.

III. LEARNING OF AUDITORY ASSOCIATIONS

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Only a small amount of experimental work has been done on the ability of Macacus monkeys to associate various auditory stimuli. This is due to the fact that the monkey, in contrast to other types of differentiation, has extreme difficulty in learning auditory signals. All previous experiments, for example, required more than 1000 individual tests in the WGTA for an individual animal before the animal was able to definitely acquire an auditory association, in cases in which only food motivation but no punishment motivation was used. This means that, over a period of about two months, a daily experimental session of 20 individual tests of 20 min duration each had to be used.

Of interest are several other investigations made by Neff and coworkers (Bibl.12, 20, 29, 76, 77) on cats, using similar techniques as those used for monkeys. These authors first found that an extirpation of the primary auditory cortex did not prevent the cat from learning the difference between various audio frequencies. In this case, the scope of the ablation was so arranged that the entire region defined as the auditory cortex by electrophysiological methods was included. In addition, these authors found that, even the complete extirpation of the auditory cortex in accordance with electrophysical criteria and with the criterion of retrograde degeneration of the corp. geniculata medialis, did not impair the ability of the cat for differentiating various audio frequencies. However, such a complete extirpation of the primary auditory cortex rendered the cat unable to localize the direction in space from which it had just heard the tone. In another study, the same researchers expanded the scope of ablations ventralward, so that they included the region which is indispensable to the Macacus monkey for visual learning, namely the Fields 20 and 21 of the inferotemporal cortex. When using such expanded ablations, they found that the cats had lost the ability to differentiate auditory sound patterns (= tone sequences), whereas they retained the ability of discriminating sound frequencies. This loss did not occur if some portions of the actual primary auditory cortex were excluded from the ablation. This results in the interesting finding that, in the cat, the same cortex is involved for differentiation of sound patterns as the one involved in monkeys for visual differentiation. It is impossible to state definitely at present whether this constitutes a contradiction with the results obtained in monkeys. Similarly, no statements can be made on whether the inferotemporal cortex of the cat has the same critical significance for visual discrimination learning as in the monkey,

since no comparative experiments on cats were made. As mentioned above, Weiskrantz and Mishkin (Bibl.120) extirpated in several monkeys only the inferotemporal cortex and found no impairment of the ability for auditory /174 discrimination; Weiskrantz and Mishkin did not test the monkeys for discrimination of sound patterns but only for discrimination between white noise and a certain sound frequency. Consequently, conditions analogous to cat experiments could be obtained only if it were possible to demonstrate that inferotemporal-operated monkeys, with simultaneous lesions of the auditory cortex, are unable to differentiate complex sound patterns. In this connection, a mention of the other experimental groups of the Weiskrantz-Mishkin study is of interest. In a supplementary group of animals, the authors extirpated the "posterior temporal cortex", in which operation the primary auditory cortex was spared in accordance with the anatomic definition on the planum supratemporale, while the entire adjacent cortex of the temporal, parietal, and occipital lobes was removed. This ablation resulted in a "slight" loss of the auditory learning ability which, however, was not significant. In another group of monkeys, the two authors resected the lateral frontal cortex. They found a distinct auditory learning deficit and therefore posed the question whether, in the monkey, a secondary auditory cerebral cortex field, contrary to expectation, might be located in the frontal cortex rather than in the parieto-occipito-temporal region. The finding of an auditory learning deficit, after lesions of the frontal cortex, was not confirmed in several other reports so that there is some doubt whether this deficit is at all of a sensory nature or not. For this reason, the question of an auditory function of the frontal cortex will be discussed in more detail later in the text, in another connection.

The results of the investigations discussed in this Chapter, therefore,

should be summarized to state that no definite conclusions can be drawn with respect to the monkey nor with respect to the cat. Only further investigations will be able to decide whether "secondary or higher" auditory cortex fields can be localized and whether these possibly are located, as indicated by work on cats, in the temporal lobe or even in the same region as the higher visual cortex field.

IV. LEARNING OF OLFACTORY ASSOCIATIONS

Only a few psychophysiological investigations exist at present on this technically difficult field. Bagshaw and Pribram (Bibl.2) described in an earlier report that monkeys, after resection of the temporal lobe, ate quinine-containing food without any sign of aversion. In their original work on the temporal-brain syndrome in macaques, Klüver and Bacy (Bibl.45) mentioned that lobectomized animals have the tendency of investigating objects in a characteristic manner by sniffing. Kaada (Bibl.42) was able to prove, by electrophysiological methods, a direct connection between the bulbus olfactorius and the inferior portion of the neocortex of the temporal lobe. On the basis of these indications, Santibanez and Hamuy (Bibl.103) trained *Macacus* monkeys to acquire olfactory associations. The test was made with the WGTA. Approximately at the level of the animal's head, a vertical plate with two circular holes was placed in the selection chamber of the WGTA; behind these holes small hanging doors, made of wire screening, were so attached that the animal was able to push them aside. A small wad of cotton, impregnated with orange extract, and another piece of cotton with vanilla extract were attached to the lower end of the two doors outside of the field of view of the animal, once on the left-hand side and then on the right-hand side. The animal was able to grasp with its hand a small peanut only after shifting the door smelling of vanilla. Conse-

quently, the entire test in every respect is similar to the principle of simultaneous selection in the visual discrimination learning sets. In all, five monkeys were operated; in two animals the ventral portion of the temporal lobe was extirpated including subcortical structures and the juxta-allocortex, whereas the lateral neocortical portion of the temporal lobe was resected in three other animals. All animals learned their task before the operation and were tested for memory after the operation. It was found that four animals, after the operation, no longer remembered the learned association but even committed more errors than in the first learning, with two animals completely unable to relearn the task in the allocated time. The number of errors committed in the test after the operation closely paralleled the extent of lesion of the inferior lateral neocortex of the temporal lobe in the individual animals. Nevertheless, it is impossible to demonstrate with certainty from these tests that the above-discussed temporal secondary higher visual field and this functionally analogous olfactory field are anatomically congruent. This is due to the fact that the ablations made by Santibanez and Hamuy are much more extensive than the classical resections made in all of the visual studies. Santibanez and Hamuy also extirpated the pole of the temporal lobe and the periamygdaloid cortex. Consequently, it may well be possible that the smallest effective ablation could be exactly restricted to this polar and periamygdaloid cortex, which would prove a function-specific separation between higher visual and higher olfactory cortex. Whether this possibility is an actual fact can be proved only by additional experimental work. Accordingly, this study by Santibanez and Hamuy yields an interesting parallel to the above-discussed auditory studies by Neff and coworkers. For auditory as well as for olfactory higher associative performances, the temporal cortex is of importance; in both cases,

an accurate localization within this cortex region has never been defined. When taking into consideration that the pole of the temporal lobe, in several reports compiled by Pribram and Krüger (Bibl.89), was closely related to the olfactory afferent system on the basis of anatomic as well as of electro- /176 physiological investigations it becomes quite obvious that emphasis must be placed on the strategically central position of the temporal lobe between the primary cortex fields of the senses of hearing, smell, and seeing. In this connection, it would be no surprise if the temporal cortex had higher associative functions of all these senses as well as of the sense of taste. For example, Hamuy and coworkers (Bibl.30), in a study with partial resection of the temporal cortex, found a proof in this direction. In ten macaques, they made a step-by-step extirpation of the inferior lateral cortex, the superior lateral cortex, and the superior polar cortex. They found a considerable visual deficit when the superior polar cortex was removed, i.e., a portion of the lateral temporal cortex which, in the above-discussed work by Pribram, Mishkin, Chow and others, had been denied as belonging into the region of associative visual functions. Conversely, they found a distinct olfactory discrimination deficit after resection of the inferior temporal cortex. These indications show that the visual function of the inferior portion of the temporal cortex, considered by many authors as being specific, must be further verified before final conclusions can be drawn.

V. LEARNING OF GUSTATORY ASSOCIATIONS

Until now, no investigations on monkeys, with the purpose of demonstrating the dependence of gustatory associations on individual cortex fields, have been made. In addition, the literature contains no technique which would be useful for training monkeys in gustatory discrimination. The old technique of Pavlov,

who introduced acids or bitter substances as conditioned stimuli into the mouth of dogs, has never^{been} applied to monkeys. Therefore, only negligibly few data are available on this question, such as those in the above-mentioned reports by Pribram and Bagshaw (Bibl.88) according to which temporal-operated animals showed a higher threshold value for the acceptability of quinine in their food.

VI. LEARNING OF TACTUAL ASSOCIATIONS

As mentioned above, the work done by Pasik et al (Bibl.83) as well as by Pribram and Barry (Bibl.85) indicates that the parieto-occipital cortex region is of importance for the ability to learn somesthetic differentiations and that, on the other hand, the temporal cortex does not participate in such functions. Wilson (Bibl.122), in an elegant investigation, was able to substantiate these earlier assumptions; therefore, this particular work will be discussed briefly. In the investigation, monkeys with resected inferotemporal cortex were compared with animals whose parieto-occipital cortex had been extirpated. The "parieto-occipital" ablation was limited by the sulcus /177 intraparietalis on the anterior and superior side, by the sulcus lunatus on the posterior side, and by the gyrus temporalis superior in the ventral direction. Consequently, in accordance with Fig.1 the ablation includes the Field No.7 as well as the superior portions of the Fields Nos.18, 19, and 22 of the Brodmann nomenclature and corresponds to the parietal standard ablation presented in Fig.2. All animals were tested with visual and tactual stimuli. In the visual discrimination learning set, covers were placed on the two feed boxes of the WGTA onto which the shape of the letter "L" or of the mirror image "L" was nailed by means of narrow strips, or else these L-shapes were replaced by short and long wooden strips. The animal had to learn to open the box on which it saw the correct "L" or which carried the long strip. For

tactual discrimination, the same markers were used, but the animals were tested in complete darkness so that they were able to recognize the difference in the two feed-box covers only by touch, similar to the way a blind person reads Braille. The animals learned both tasks before the operation and were tested for memory, after the operation. It was found that the parietal-operated animals were unable to recognize the significance of the strips on the covers after operation since they had to touch them in complete darkness; however, they were readily able to select the correct box when they were allowed to look at the situation in full light. For the inferotemporal-operated animals, exactly the opposite result was obtained. They gained no advantage from viewing the markers but were able to differentiate them in the dark by mere touch. An auxiliary finding was the fact that the parietal-operated animals showed considerable visual disorders for a short time after the operation which, in some animals, went as far as complete blindness for a period of 1 - 2 days. The author believed that these visual defects were due to a lesion of the fibers in the optical radiation which had been produced during suction drainage of adjacent portions of the occipital cortex. The finding that these parietal-operated animals, despite a lesion of the primary visual efficiency, exhibited no damage furnishes a distinct proof for the above-discussed work by Wilson and Mishkin (Bibl.123) on the differentiated effect of an ablation of the occipital cortex striatus and of the inferotemporal cortex. Consequently, this study yields the ideal picture of a double dissociation of the results: The ablation I produces the learning deficit A but not the learning deficit B, whereas the ablation II produces exactly the opposite result. In another report, Orbach and Chow (Bibl.81) demonstrated that an ablation of the primary somatic area I, i.e., of the Fields 3, 1, 2 in accordance with the Brodmann nomenclature, resulted in an

even more drastic and irreparable deficit of poor tactual discrimination than had been produced by a lesion of the secondary somatic areas, which had been extirpated in experiments by Wilson. Thus, a certain parallel exists with the above-discussed interactions between primary auditory and adjacent secondary auditory cortex, as proved in cat experiments.

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VII. SYMBOLIC PSYCHIC PROCESSES

In 1936, Jacobsen (Bibl.38) reported that frontal-brain-operated macaques completely lost the ability for delayed reactions, that emotional stress reactions which had possibly been produced before the operation were drastically weakened, but that the ability of learning visual discrimination was not at all impaired. On the other hand, Kennard et al (Bibl.43) distinctly described hyperactivity as a further sequel of ablations of the frontal brain. This hyperactivity manifests itself in a striking restless circling of their cages by the animals, similar as seen in lions in captivity. Based on these findings, the research on the frontal-brain syndrome in macaques centered especially on the following points: Can these individual functions be ascribed to anatomically separate cortex areas? Which is the smallest effective ablation causing a loss of the delayed reaction? Should the function of the delayed reaction be attributed to additional cortex areas, located outside of the frontal brain, or possibly also to subcortical structures? How can the psychological significance of the loss of delayed reaction be characterized more closely by a possible modification of the test methods? Do frontal-brain ablations, besides the loss of delayed reaction, result in no other behavior deficits, specifically with respect to other symbolic psychic or associative processes?

Cortical Focal Region of Delayed Reaction

In his first investigations, Jacobsen removed the entire prefrontal cortex located anterior to a line "several millimeters" in front of the frontal boundary line of the premotor cortex (Field 4 of Fig.2). Later, he proved that an extirpation of the premotor and the motor cortex did not lead to a loss in the delayed reaction (Bibl.40). Work done in the next decade, in an attempt of assigning a more narrow focal field, within the prefrontal agranular cortex, to the function of delayed reaction, led to contradictory results. Only later investigations were able to yield a better clarification of this question. Pribram et al (Bibl.87) compared the effect of an ablation of the ventromedial cortex in four baboons and the effect of an ablation of the dorsolateral frontal cortex in three other baboons with the behavior of two unoperated animals. The dorsolateral operation comprised the lateral and dorsal frontal cortex rostrally and dorsally from the knee and the lower branch of the sulcus arcuatus (U-shape sulcus, open toward the front and located in the frontal lobe shown in Fig.2). In the ventromedial operation, the lateral frontal cortex was left completely untouched while the ventral and medial cortices of both frontal lobes were almost fully extirpated. The authors definitely found that an /179 ablation of the ventromedial cortex hardly interfered (or only slightly in some cases) with the ability for delayed reaction, whereas an ablation of the dorsolateral cortex led to a complete loss of this ability. Blum (Bibl.7) further subdivided this dorsolateral cortex by minor partial ablations in six macaques and, on the basis of his study, postulated that the critical field for the delayed reaction could be restricted to the region on both sides and in the depth of the sulcus principalis of the frontal lobe (sulcus principalis = longitudinal sulcus within the sulcus arcuatus or midgracile sulcus on the dorsolateral

area of the frontal lobe, in accordance with Fig.1). Mishkin (Bibl.69) substantiated the same finding with a larger group of ten macaques. Figure 5,

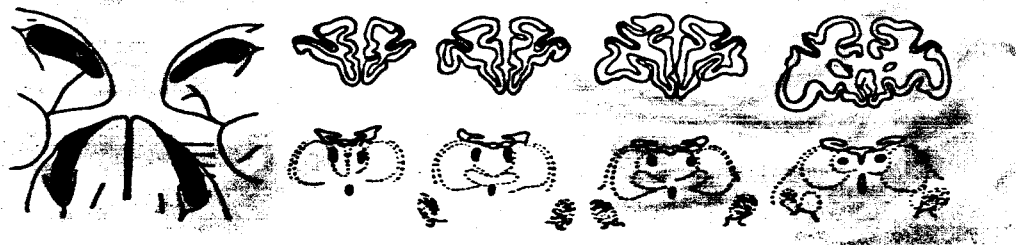


Fig.5 - Focal Region of the Ability for Delayed Reactions, according to Mishkin (Bibl.69)

which was produced according to data by Mishkin (Bibl.69), gives a general view over this more narrow focal region governing the ability for delayed reaction. In addition to a reconstruction of the ablation, the illustration also gives cross sections of the ablation as well as indications of the thalamic retrograde degeneration foci. An interesting point is the complete ablation of the cortex in the depths of the sulcus principalis, as shown on hand of the cross sections.

In how far the frontal optical fields (dorsal portions of Area 6 in Fig.2) may be excluded from this focal field can be decided only indirectly from previous studies. Neither Mishkin nor Blum had ever separately ablated this field in any of their animals. Pribram (Bibl.90), who made a specific study on the ablation of the frontal optical fields, found a strong deficit in the learning of delayed reactions, but his ablations comprised also a relatively large portion of the field along the sulcus principalis which had been identified by Mishkin and Blum, independently of each other, as the focal field for delayed reactions and which anyhow cannot be counted as belonging to the frontal optical fields. Consequently, it may be summarily stated at present that the dorso-lateral cortex, within the leg of the sulcus arcuatus, can be placed at the center of the function of delayed reactions, whereas the optical fields cau-

dally adjacent to this region can be excluded from the function with a large /180 degree of probability although not with complete certainty. This still leaves the question open as to the stricter localization of the two other mentioned main components of the frontal-brain syndrome in macaques, namely hyperactivity and changes in emotional behavior. In both cases, it is not absolutely possible to separate individual focal fields for these functions from the focal field of delayed reactions. So far as hyperactivity is concerned, French (Bibl.26) found that this is released mainly by a resection of Area 9 of the agranular frontal cortex, i.e., of a field in which also the critical focus for the delayed reaction is located. According to the same author, a resection of Area 6, i.e., of the optical fields, produces no hyperactivity. Conversely, various other authors such as Ruch and Shenkin (Bibl.102) as well as Livingstone et al (Bibl.51) demonstrated at an earlier date that specifically an ablation of Area 13 of the Macacus brain (cortex area resting on top of the orbita, only partly visible in Fig.2) produces an intense hyperactivity which apparently is even greater than that produced by a lesion of the dorsolateral cortex area. In addition, Richter and Hines (Bibl.94) in experiments with macaques, as well as Mettler (Bibl.53) in experiments with baboons and Mettler (Bibl.54) in experiments with cats, found that an ablation of the nucleus caudatus in addition to an ablation of the dorsolateral cortex will further intensify the hyperactivity. These results lead to the conclusion that not only large portions of the frontal cortex but also subcortical structures of the striatum participate in the regulation of normal spontaneous activity. In a similar manner, no narrow field within the frontal lobe can be pinpointed as being responsible for the changes in emotionality. In his first report, Jacobsen (Bibl.39) described that a chimpanzee became "neurotic" before the

operation because its tasks were too difficult for him. The more such tests progressed the more excited became the animal; each error that it committed made it extremely furious. It stamped on the floor, whimpered, and cried, accompanied by frequent defecation and urination. After bilateral prefrontal lobectomy, as mentioned by the author, it seemed "as though the animal had shifted his entire burden to its master"; from now on, it reacted to any difficult test situation and even to any error with the same disinterested equanimity. Besides this report, the literature contains no further systematic studies on the effect of frontal-brain ablations on "experimental neuroses" despite the fact that it was exactly the report by Jacobsen which induced Edgas Moniz to introduce frontal lobotomy into neurosurgery. It is true that other types of psychoexperimental techniques were applied, such as the over-trained fear of a given object or situation or the conditioned escape from stimuli signaling pain. However, these studies showed that differing changes in emotionality, including abatement found by Jacobsen in chimpanzees after frontal lobectomy, will occur even when a number of other structures, located 181 outside the frontal brain, are extirpated. In addition, Harlow et al (Bibl.34), in contrast to Jacobsen, found no decrease in the spontaneous emotionality of monkeys when they encountered failure in a given test situation, after extirpation of the frontal cortex. A number of reports, of which only those by Waterhouse, Lichtenstein, Weiskrantz, and Pribram and Weiskrantz (Bibl.115, 50, 119, 93) need be mentioned here, gave information on the complexity of this special problem complex which will not be further discussed here. In summary, it may be stated with respect to attempts at a localized subdivision of the frontal-brain syndrome in macaques, that only the delayed reaction deficit can be assigned a more narrow focal field but not the hyper-

activity or the disturbances in emotional behavior.

Structures Outside the Frontal Lobe and Delayed Reaction

Many of the above-discussed reports on the effect of an extirpation of the posterior cortex on the learning of sensory associations described experiments in which the animals were tested, after operation, as to their ability for delayed reactions. In none of the reports could a deficit of this function, after extirpation of the posterior cortex, be proved. Conversely, investigations on the significance of subcortical structures for this complex performance yielded a different result. A first indication for the assumption that subcortical structures participate in the performance of delayed reaction was obtained in a study by Wade (Bibl.113), in which the effect of circumcision of the frontal cortex was compared with that of lobotomy. The separation of the frontal cortex from the adjacent cortex by circumcision had no detrimental effect on the delayed reaction, in contrast to lobotomy in which the connections to the subcortex were cut through. Since extensive projections exist between the frontal cortex, specifically between the dorsolateral cortex along the sulcus principalis and the parvocellular portion of the nucleus dorsomediales of the thalamus, it seemed logical to clarify the possible participation of this nuclear region in the above function. Chow (Bibl.16) as well as Peters et al (Bibl.84) made extensive stereotactic electrolytical ablations in this structure, but in none of the cases found any loss of delayed reaction. According to work done by Harman et al (Bibl.35) and Mettler et al (Bibl.55) direct anatomic connections exist also between the frontal cortex and the nucleus caudatus. That the nucleus caudatus actually is of significance for the delayed reaction function was demonstrated in investigations by Rosvold and

Delgado (Bibl.98) and by Rosvold et al (Bibl.99) who all showed that, after coagulation within the head of the nucleus caudatus, the animals committed a larger number of errors in the delayed alternation test. Other investigations by Bättig and Rosvold (Bibl.3) and by Migler (Bibl.58) indicated the probability that the deficit in delayed reaction becomes greater the larger the ablations in the nucleus caudatus and that, at complete destruction of the nucleus, a /182 deficit must be expected which will be just as complete as that produced by an ablation of the dorsolateral frontal cortex. This expectation was actually and fully confirmed in recent work by Dean and Davis (Bibl.19). After subtotal destruction of the caudatus, these authors encountered a complete loss of the ability for delayed reactions in the Macacus monkey. Similarly, work done by Migler (Bibl.58) makes it quite probable that a dissection of the frontal portion of the corpus callosum also impairs the delayed reaction performance. Since this author removed the nucleus caudatus from the medial end after dissection of the corpus callosum, by suction drainage, he also used operated control animals with a simple dissection of the corpus callosum in his studies. These operated control animals later learned the delayed reaction more rapidly than the caudectomized animals, but more slowly than the unoperated control animals. This fact becomes of even greater importance in the light of Rosvold's finding (Bibl.101) that crossed fibers run through the corpus callosum, coming from the dorsolateral frontal cortex and going toward the opposite-side nucleus caudatus. In summary, it can be concluded that, outside of the dorsolateral frontal cortex, no other cortex portion of the Macacus brain participates in the function of delayed reaction but that the nucleus caudatus plays an important role for this function, which leads to the question in how far additional sub-cortical structures may be involved in this function.

Psychological Reasons for the Failure of Frontal-Brain-Operated Monkeys in Delayed-Reaction Tests

Several individual factors which may be responsible for such failure in operated monkeys, were investigated in numerous experiments. The fact that the time elapsed from presentation of the stimulus to reaction cannot be bridged would indicate that the operated animals have suffered a loss of memory. However, it had been mentioned above that the learning of visual discriminations, in which a given animal had to remember his tasks from one day to another, gave no greater difficulty to a frontal-brain-damaged animal than to a normal animal. The behavior deficit of the frontal-brain-damaged animal, therefore, was denoted by terms such as loss of "short-time memory" or of "instantaneous memory", which is to indicate that, in addition to the conventional type of memory, there exists a second form of memory required for bridging very short periods of time. On the basis of such an assumption, it could be expected that a delayed-reaction task would be more difficult for an operated monkey the longer the delay had lasted. Meyer et al (Bibl.56) compared the performance for delayed periods of 5, 10, 20, and 40 sec and found that operated monkeys always failed, no matter how long the delay time had been and no matter whether an attempt had been made to increase the delay time successively from 5 to 40 sec or else whether short and long delay times alternated in a random sequence. A study by Mishkin and/183 Weiskrantz (Bibl.71), however, indicates that this conclusion is no longer valid for delay times of less than 5 sec. The operated animals, in this experiment, were able to bridge delay periods which had gradually been increased from 0 to 8 sec but were unable to do so when a delay of 8 sec was abruptly introduced. It should be mentioned that, in this investigation, no screen was lowered in front of the animal between application of the stimulus and reaction and also

that the reward following the reaction, rather than the reaction itself, had been delayed. Consequently, this finding complements earlier data on the failure in delayed reactions. Similarly, a delay in reward instead of in the reaction resulted in the failure of frontal-brain-operated monkeys. The question in how far the lowering of a screen in front of the animal during the delay in order to prevent it from seeing the stimulus or the locus of reaction might be an important criterion, has been partially answered in a report by Bättig et al (Bibl.3). In their experiments, a screen was lowered in front of the animal during the delay and the delay itself was gradually increased from 0 to 5 sec. As soon as the screen had been lowered, even if there was only a brief lowering or raising, i.e., a delay of "0 sec", the operated monkeys failed completely even if the training with each animal was prolonged over a period of weeks. If, conversely, the screen was not lowered and the animals were merely prevented from reacting during the delay by the experimenter holding down the cardboard covers on the feed boxes, the operated animals mastered all delay times up to 5 sec. Nevertheless, even for this easier form of delayed reaction they required many more experiments than could be expected from a normal monkey. An explanation for this finding was obtained from observing the experimental animals. These were able to react correctly after the delay only if they "forced themselves" to remain sitting behind the correct feed hole during the entire delay. At first, they had to learn to remain sitting, which was quite difficult for them since they all were hyperactive. For normal animals, this problem constitutes no difficulty. Primarily, such animals are not hyperactive and, secondly, they are able to find the correct feeding place even if they had climbed around the cage during the time of delay. This indicates that operated macaques are unable to bridge a true delay in which they are physically sepa-

rated from the loci of reward and reaction. If they are not physically separated from the points of reaction and stimulus, they will learn to devise for themselves a sort of "mental crutch", by remaining sitting in front of the correct stimulus until the delay has passed; of course, here one can no longer speak of a true delay, since the stimulus presented before the delay has been substituted by their remaining seated at the proper spot. Thus, the above-mentioned concept of "short-time" ("recent") or "instantaneous memory", although quite unsatisfactory in its formulation, will remain furthermore valid. As another factor, it was investigated in how far the restless activity of frontal-brain-damaged monkeys may contribute to the failure in delayed reactions. Considered from this viewpoint, one could no longer speak of a loss of short-time memory but rather of a loss of attention and "ability to concentrate", due to the continuous reacting to even the most minor intercurrent stimulus.

Meyer et al (Bibl.56) believed it possible to exclude such a correlation since they observed that a unilateral extirpation of the frontal cortex resulted in a distinct hyperactivity but not in a failure in delayed reaction. Similarly, Harlow et al (Bibl.34) came to the same conclusion and also found that the specific failure of the operated monkey has no relation to hyperactivity nor to the operation-induced changes in emotional behavior. However, other authors later came to different conclusions with respect to the role of hyperactivity in the behavior of brain-damaged monkeys. Malmö (Bibl.52) correlated the degree of activity during delay with success or failure in subsequent delayed reaction. He found that a false reaction of the experimental animal occurred earlier, the more active the animal had been in the delay period preceding the reaction. He also found that the animals were more active during the delay if they had spent this delay period in a lighted rather than in a dark cage. Wade, Pribram, and

Mishkin et al (Bibl.112, 86, 63) followed up on this concept by attempting to increase the performance of operated animals by the use of sedative barbiturates. In all three investigations they obtained a distinctly improved performance of the operated monkeys under the effect of the barbiturate, although the performance of unoperated animals was not even faintly equaled in any of the cases. Dean and Davis (Bibl.19) and Davis (Bibl.18) obtained the same result, not only on frontal-brain-damaged monkeys but also on monkeys with caudate-nucleus lesions. It was of interest that they found this effect not only as a consequence of the use of barbiturate sedatives but also after giving exciting drugs such as phenyldiethyldiacetate. These correlations were compiled by Stanley and Jaynes (Bibl.109) in a general survey, together with other findings, and induced them to interpret the behavioral deficit of frontal-brain-operated monkeys as a loss of inhibitions. Accordingly, operated monkeys would be no longer able to inhibit reaction and attention to intercurrent afferent stimulations during the delay, which would eradicate the "memory trace" which is necessary for a correct delayed reaction. These authors made the assumption that such a loss in inhibition can be attributed to a lesion of the frontal "suppressor areas" as they had been postulated at that time, on the basis of electrophysiological studies.

Another point investigated was the type of motivation for reaction. /185
Whereas all above authors rewarded their animals for a correct reaction by giving them food, Miles and Rosvold (Bibl.59) rewarded their animals by withholding electric shocks when the reaction was correct, while punishing false reactions by such pain stimuli. Since the operated animals failed also under these conditions, it cannot be assumed that the operation had caused a weakening of the food motivation, secondarily producing failure in delayed reactions.

The hypothesis that monkeys with frontal-brain lesions lose their discrimination and recognition ability for the stimulus preceding the delay was investigated in additional tests on delayed reaction. Mishkin and Pribram (Bibl.68) found that the performance of operated animals was not influenced in cases in which the animals had been shown the reward before the delay at a certain spot (direct method) or whether the correct spot had merely been indicated to the animal by means of a "food signal" (any object will do) before the delay (indirect method). Conversely, the authors were able to facilitate the task for the operated animals by using only one instead of two stimuli per selection situation. This one stimulating object was placed on a single selection hole at the center (or, if two holes were present, in the middle between the two). In the first case, the quality of the stimulus indicated whether a reward had been placed into the single hole or not, and in the other case whether the reward was located to the left or right of the stimulus. Of these two tasks, only the one in which a single hole is used constitutes a facilitation. From this, it should be concluded that frontal-operated monkeys have special difficulty to "memorize" the significance of "left and right" beyond a time delay. A similar conclusion was drawn by Meyer et al (Bibl.56) who found that frontal-operated animals are unable to remember the positional significance of a stimulus beyond the time of delay. In itself, this explanation would be quite logical when considering the behavior of monkeys which, because of their enforced circling in the cage, no doubt have difficulty in evaluating the spatial significance of left and right. However, such a conclusion cannot be drawn with certainty from these two reports since it still could be possible that other factors play a supplementary role such as, for example, the fact that a single stimulus placed at the center of the selection board represents a simpler stimu-

lus situation than two stimuli, a negative and a positive stimulus, placed on the left and right sides of the selection board. Pribram and Mishkin /186
(Bibl.92) by the use of a logical test setup, clearly excluded the possibility that the operation caused the animals to lose the ability to "memorize" the left-right significance of stimuli beyond the delay itself. The authors placed two objects of different type, randomly interchanged, on the left and right feed hole. No matter where the objects were laying, the animals had to select alternately the object A and B. In this case, left or right no longer had any significance and the task merely consisted in avoiding the object under which food had been hidden in the preceding test. The operated animals failed completely with this type of arrangement and their performance hardly improved in the course of prolonged training. These investigations seem to indicate that recognition of the stimulus, offered before the delay, may play an important role for the failure but that the decisive factor for this recognition possibility still is obscure.

In several other investigations, attempts were made to vary the reaction itself in delayed-reaction tests. Mishkin and Pribram (Bibl.67) made the operated animals reach toward the top or bottom instead of toward left or right, and in a third type of test they required the animals to reach alternately toward the single feeding place and not to reach at all in the following test. The operated monkeys only learned the alternation of reaching and not-reaching, but (as mentioned above) this result can also be explained by the fact that, in this type of test, not only the reaction itself but also the preceding stimulus had been varied in a critical manner. This leaves the question open as to whether the type of reaction, in addition to the characteristics of the predelay stimulus, comprises critical factors for the failure of operated monkeys.

As another possibility, it was suggested that operated monkeys had a lower food motivation or that they were more quickly discouraged by unrewarded erroneous selections. Finan (Bibl.24) established this hypothesis after he found that operated animals improved their performance whenever he fed them before the delay at the same spot at which the correct reaction was to take place after the delay. However, this finding can be traced to the fact that, in this procedure, the stimulus offered before the delay was reinforced in that the monkeys, before the delay, not only had seen that the reward (for example) was placed toward the left but also to the fact that their attention was more centered on this particular spot by having been given the previous reward. That this explanation must be considered valid is proved by the work of Harlow et al (Bibl.34) who gave additional rewards to the animals during the test, which had no correlation with the test itself and did not improve the performance of the operated monkeys. A final conclusion, based on these investigations, indicates that the failure of frontal-brain-damaged monkeys in the delayed reaction tests is due to their inability of bridging short periods of time. The decreased attention produced by the hyperactivity as well as the content of the stimulus preceding the main stimulus represent additional factors. It is impossible to give a /187 more accurate psychological definition of this failure at present.

Duration of the Behavior Deficit in Monkeys with Frontal-Brain Lesion

A number of reports uniformly indicate that, after total excision of the frontal cortex in adult animals, no remission of the ability to solve delayed tasks occurs after prolonged periods of time. The above-mentioned work by Harlow et al (Bibl.34) showed no such remission, even eight months after the operation. Brush and Mishkin (Bibl.9) investigated animals in which the opera-

tion had been performed many years before and came to the same result. This raises another question, namely how early after operation does the behavior deficit disappear. Forgays (Bibl.25), on the basis of his own experiments on rats and on the basis of the clinical literature, postulated that an effect, after lesion of the brain substance, occurs only with a certain latency. Orbach (Bibl.79) checked more closely on this hypothesis by operating monkeys in two steps. In the first session, only the bore holes were drilled into the cranium; in the second session, the frontal lobotomy was performed through these holes under light ether anesthesia (ether rausch). With this procedure, it was possible to test the animals as early as 1.5 hrs after the decisive intervention without having to wait for recuperation from a deep general narcosis. The author encountered the full effect of the operation already 1.5 hrs after the intervention and, therefore, concluded that the results obtained by Forgays and other authors were due to the fact that their animals had remained for a relatively long time after the operation under the barbiturate effect of the narcosis. This assumption seems especially plausible since barbiturates are able to improve the performance of operated monkeys, as mentioned above.

Sensory Discrimination in Monkeys with Frontal-Brain Lesion

Jacobsen (Bibl.37) and, long before him Bianchi (Bibl.5) and Ferrier (Bibl.23), assumed that the anterior frontal cortex serves exclusively for complex psychic but not for associative sensory functions, whereas the posterior cortex must be considered the true associative sensory cortex of the monkey. This opinion remained unquestioned for a long period of time since it was never challenged or, at least, never appeared to be challenged. After ablation of the frontal cortex it was always found that the animals were unable to postpone

reactions and that disturbances of the sensory discrimination learning occurred every time after ablation of the posterior cortex.

More recently, however, it was demonstrated that, under special conditions, disorders in discrimination learning occurred also in frontal-brain-operated monkeys and that similar findings had really been contained in earlier reports but had never been properly regarded. Since, however, there is now greater clarity as to the nature of such findings, it should be mentioned here that such behavior deficits are only apparently of a sensory nature. The behavior deficits in question must be due to a failure of other, and probably higher, more complex functions as is the case for the inability to postpone reactions. An earlier report by Pribram et al (Bibl.87) contains the finding that frontal-brain-operated monkeys learn visual discrimination more slowly after the operation than do normal animals, but this finding had never been properly evaluated. Harlow and Dagnon (Bibl.32) also found that monkeys, after the operation, had more difficulty to relearn from one to another - diametrically opposite - significance of visual signals than did unoperated monkeys. The authors considered this a loss of some higher intellectual function rather than a sensory discrimination deficit. /188

A more recent investigation by Bättig et al (Bibl.4) contains a direct indication as to the nature of such visual discrimination deficit in frontal-operated monkeys. In these tests, operated monkeys learned an ordinary visual discrimination normally in one of the test variants and more slowly in the other variant. The classical simultaneous differentiation of two visual patterns, placed simultaneously on the selection board, gave the animals no difficulty. However, as soon as the stimuli were successively presented, i.e., as soon as in the individual tests there was only a positive stimulus present

which covered the food while in the other tests the negative card was placed on an empty feed box, the same animals had extreme difficulty to keep from uncovering the feed box when looking at the negative card. It is of interest that this investigation showed the same syndrome, but in an attenuated form, for caudate-nucleus-operated animals, which means that a parallel exists with investigations on the ability for delayed reaction after ablation of the frontal cortex and of the nucleus caudatus. Similarly, Brush and Mishkin (Bibl.9) were able to show that a failure of the frontal-operated monkey in discrimination tests may occur as a consequence of modified test procedures. These authors trained their monkeys to differentiate a large number of various objects in a serial test extending over months. Each day, new objects were used and only a few individual tests were given in each session. In the first individual test, two objects were always laying on the selection board, in which case food had been placed either under both objects or under none. In all subsequent individual tests, food was placed under the object which had been spontaneously selected in the first individual test and had never been seen previously, but only if food had been there also in the first individual test. Conversely, there was no food under the object if no food had been under in the first test. It was just as easy for the frontal-damaged monkeys to learn the variant in which food was always hidden under the selected object, as it was for the unoperated monkeys. Conversely, they learned the other variant, namely that no food was under the object, much more slowly. The first finding by Bättig could be interpreted in that frontal-operated animals have a inhibition deficit in the Pavlov terminology since they learned only slowly to inhibit the reaction to an unrewarded negative stimulus. The studies made by Brush and Mishkin /189 could be interpreted similarly, by stating that operated animals have a greater

perseveration for an initially preferred stimulus. In both cases, a true sensory discrimination deficit can be excluded since the monkeys, under proper test prerequisites, were able to discriminate the same objects and painted cards.

Similar parallels exist for other sensory modalities. Weiskrantz and Mishkin (Bibl.120) found that operated monkeys were much slower in learning correct reactions to successively presented auditory stimuli than unoperated monkeys. In the mentioned investigation by Bättig et al (Bibl.4) the same technique was used for proving a loss in the auditory discrimination ability. However, the same monkeys learned to differentiate the same sounds when, in another auditory test, they had to learn to depress a left-hand lever for one signal and a right-hand lever for the other signal (automatic WGTA). Blum (Bibl.7), using this procedure of simultaneous left or right selection, found a learning deficit in the operated animals; however, as a supplementary food motivation, he used electric shocks with which he punished incorrect selections. This result could be interpreted in the same sense as the above-discussed data in that the shock, in a normal animal, with normal inhibitions, suppresses the uncorrect reactions much more rapidly than in damaged operated animals. This interpretation gains in probability when using a study by Waterhouse (Bibl.115) as comparison. This author also trained the animals to open either the left or right one of two feed boxes, on receiving visual or acoustic signals. Opening of the correct box was rewarded while opening of the wrong box, as in Blum's investigations, was punished by electric shocks. Under this condition, the operated animals committed more errors than the control animals, not only in responding to acoustical but also in responding to visual signals. In the discrimination of tactual stimuli, similar complex conditions occurred. Usually, the test proceeds so that the animals can only touch a given feed box but cannot

see it and, by using the surface condition of the box cover as a guide, must decide whether they want to open the box or not. Since these animals, even when two boxes are present, ordinarily touch only one of the two covers with both hands at the same time, the conditions are similar to those in the successive test for discrimination of sensory stimuli of different modalities. Ettlinger and Wegener (Bibl.21) found that frontal-operated animals were much slower in learning such a task than were unoperated monkeys. Rosvold et al (Bibl.100) varied the method in such a manner that the box covers were more difficult to open; in this variation, the operated monkeys learned just as rapidly as the unoperated monkeys. Allen (Bibl.1) also found that dogs with prefrontal ablations cannot make as fine an olfactory differentiation. On the basis of previous discussions, it could be expected that this result is non-specific in a similar manner despite the fact that no experimental proof exists up to now. Brutkowski, Konorski et al (Bibl.10) systematically studied the nature of such behavior deficits in the dog. They trained the animals before the operation not to react to certain auditory stimuli but to react instead to other auditory stimuli. After the operation, the animals committed many errors but only insofar as they again reacted to the unrewarded negative stimuli. The authors believed that this deficit again constitutes a loss in inhibition. This loss, however, in contrast to the loss in delayed reactions, was only temporary and less striking. The authors, therefore, believe that the loss in ability of delaying reactions and the loss in inhibition can be attributed to damage of two mutually independent functions and may even be linked to locally separate focal regions within the frontal cortex. Other authors of the same Polish research groups substantiated these assumptions with varying test procedures. Lawicka's dogs (Bibl.49) had to bark before they received food, but

the barking helped only if it was done after receiving a positive stimulus. After the operation, the dogs also barked after unrewarded negative stimuli. Brutkowski (Bibl.11) obtained similar results with the classical salivary conditioned reflexes of Pavlov's technique.

These investigations all show that an ablation of the frontal cortex will not damage the discrimination ability for sensory stimuli but that, conversely, this operation does not only cancel the ability of delaying reactions. Rather, the frontal-brain syndrome of the monkey and of the dog has a much more complex nature than had been originally assumed. Despite the fact that a loss in inhibition may be an explanation for some of the findings, such explanation can be maintained only with difficulty for other cases, as shown by a few additional examples.

Mishkin and Weiskrantz (Bibl.72), on operated monkeys, determined the critical frequency at which individual light flashes subjectively coalesce into a single light source. The authors found that this critical fusion frequency is higher in operated monkeys than in the control animals. For this case, the theory of an inhibition loss can be maintained only by making speculative attempts at an explanation. Meyer and Settlage (Bibl.57) observed the behavior/191 of animals when they were faced with four feed boxes of which either one or the other was supplied with food at random. The searching behavior of the operated animals was less stereotype than that of the control animals. Thus, the operated animals showed much less perserverance in trying to open a certain box whenever this systematic game was unsuccessful than was shown by the control animals. Despite the fact that the operated animals retained such hypotheses for solving an unsolvable problem in a less stereotype manner, they were able to avoid a repetition of a previously tried but unsuccessful hypothesis.

French (Bibl.27) found that operated monkeys did not pay much attention to a lever installed in their cage whose manipulation either had no consequences or merely increased the illumination in the cage. These results are also difficult to explain by the concept of inhibition loss. From the psychological theoretical viewpoint, it would also be quite difficult to find a bridge to the hyperactivity or to the loss of the ability for delaying reactions.

VIII. DISCUSSION AND TRENDS OF THE FINDINGS FOR BRAIN-DAMAGED HUMANS

As the most important factor, it can be concluded from all of the above-discussed investigations that the higher cortex of the monkey, at least to a certain degree, actually is specialized in a function-specific manner. As postulated earlier by Jacobsen (Bibl.37), higher complex psychic functions must be attributed to the anterior cortex, whereas the posterior cortex governs the associative sensory functions. In both cases, however, an accurate subdivision of the cortex into focal regions for individual psychic functions is not always possible. Circumscribed cortical fields can be defined with relative certainty only for the somatosensory and visual discrimination ability. The focal zone for olfactory and gustatory discrimination possibly overlaps the cortex area for visual discrimination. No conclusions can be drawn at present as to the existence of a specific brain field for the auditory discrimination in monkeys. In addition, none of the cases permitted an interpretation of the mechanism of recuperation of an associative function after lesion of the critical brain field. The psychic frontal-brain syndrome of the monkey is much more complex than had originally been assumed. The psychological background of the most striking deficit in frontal-brain-operated monkeys, namely the irreparable failure in delayed-reaction tests, has never been explained to date. The com-

plex and manifold nature of the frontal-brain syndrome in monkeys clearly indicates that either a number of functions may be concentrated in the same brain field or that a possible functional correlation of such widely differing performances is psychologically unexplainable by present available means. These/192 facts partly contradict the rigid anatomic-functional concept on which many of the above-discussed investigations were based.

In addition to new discoveries which, in many cases, were able to give an experimental and scientific proof for earlier hypotheses based on anatomic and physiological studies, one of the main advances in the field is the successive refining of the psycho-experimental methodics in animal experiments. Such methods permit a concentrated testing of the most widely varying psychic functions. This will furnish a tool which, in time, may help in producing more progress than ever had been possible in the field of psychophysiology and the increasingly more important field of psychopharmacology. The advances made in the development of psycho-experimental methodics are due to a number of individual factors. Experiments on chained animals, as made by Pavlov and his students, were followed by experiments on freely moving animals. The rigid methodics of Pavlov's time was relaxed somewhat, so that the individual experiment is increasingly directed toward the goal of the specific psychic function under investigation rather than toward abstract psychological function theories. The animal is no longer considered a helpless subject whose behavior is determined by passively absorbed sensory impressions and their regular work-up in the central nervous system, but rather an organism which has its endogenous "will power and decision" and, to a limited extent, even its own "reasoning" faculty.

A discussion of these investigations would not be complete without a brief

1 indication of the results obtained in physiological investigations on brain-
2 operated human subjects.

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5 Unfortunately, such a comparison is difficult to make because of various
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7 circumstances, and cannot give the expected parallels. A primary difficulty in
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9 experiments with human subjects lies in the fact that the strict control condi-
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11 tions of monkey experiments can be satisfied only in rare cases. It is seldom
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13 that a human subject can be tested with the same methodics before and after an
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15 ablation of the cortex. If the lesion of the cortex was due to an accident, no
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17 previous examinations are in existence; if such a lesion was surgically pro-
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19 duced, the functional state had been pathological already before the operation.
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21 Only on rare occasions can entire groups of individuals with the same brain-
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23 trauma anamnesis be compared, and findings on single individuals furnish only a
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25 few statistically provable results. A similar difficulty exists in the fact
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27 that the educational level, which has a great influence on the performance in
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29 such tests, varies greatly from individual to individual. In addition to these
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31 difficulties which are due to the nature of the problem, there are also methodi-
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33 cal differences in the available experimental problem complex for brain-damaged
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35 human or animal subjects. In most cases, the tests for brain-damaged human /193
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37 subjects were much more complex than those used for monkeys. The widely used
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39 intelligence tests do not concentrate specifically on an individual psychologi-
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41 cal function but rather on associations of all different sensory modalities,
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43 memory, higher psychic functions, etc. Therefore, it is not surprising that we
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45 know actually less on the functional organism of the human cortex than on that
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47 of the monkey cortex. For this reason, only a few experimental investigations
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49 which are comparable in method with animal experiments will be mentioned in
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51 this connection. For a more detailed orientation as to psycho-experimental
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1 investigations on brain-damaged humans, investigations on the speech center,
2 and on dominance of one cortex hemisphere, reference is made to the pertaining
3 literature (Bibl.82).

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5 The need for equivalent psychological tests, before and after brain trauma,
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7 was more or less satisfied in an extensive study by Weinstein and Teuber
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9 (Bibl.117) on the general intelligence after brain lesion. These authors made
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11 use of the intelligence tests ordinarily used by the American Armed Forces in
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13 their selective service system for testing recruits. A large number of soldiers
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15 were retested with the same intelligence tests ten years after a brain injury
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17 received during the war and were then compared with other soldiers who had suf-
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19 fered injury to the peripheral nerves but not to the brain. It was found that
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21 specifically brain-damaged soldiers who had suffered war injury to the parietal
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23 or temporal cortex showed a measurable and significant loss of intelligence.
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25 In addition, the authors found that, in all brain-damaged subjects as a group,
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27 the performance in intelligence had less increased since their original re-
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29 cruiting than had been the case in the controls. This apparent proof for the
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31 greater importance of the parietal and temporal cortex than of the frontal cor-
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33 tex for general intelligence did not agree with many other reports. Other au-
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35 thors such as Rosvold and Mishkin (Bibl.97) as well as Hoyt, Elliott and Hebb
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37 (Bibl.36) also tested soldiers who had been given the same intelligence test
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39 before the war and found a greater loss of intelligence after lesion of the
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41 frontal cortex. This comparison may give a general hint as to the difficulty
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43 of the problem involved. An explanation for the difference in the findings may
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45 be offered by the fact that, in the experiments by Weinstein and Teuber, many
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47 more individual subjects were tested and that such a procedure was more effec-
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49 tive in avoiding the influence of random events on the overall result. In
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1 addition, the technique of the point system in evaluating the intelligence was
2 not uniform in the various studies. A general conclusion which can be drawn
3 from these and other investigations on intelligence, seems to be that a true
4 intelligence loss occurs after cortex ablations but that the question as to the
5 equal or different importance of various cortex regions for general intelligence
6 is far from being answered. When going through the literature in a search for
7 investigations which were mainly concerned with the performance within indi- /194
8 vidual sensory modalities, the above-mentioned difficulty will always be en-
9 countered, namely that human subjects were generally tested in experiments
10 which simultaneously covered visual, acoustic, verbal, tactual associations,
11 etc., without a clear separation of the items. This makes it very difficult to
12 draw the conclusion that individual brain fields in humans are responsible for
13 specialized performances. Therefore, we can discuss only a few investigations
14 which do not exhibit this particular drawback.

15 According to Milner (Bibl.60), a disturbance in the associability for
16 visual stimuli will occur after ablations in the temporal lobe. The same author
17 (Bibl.62) demonstrated in a later work, in which she tested a much larger
18 collective, that the intactness of the temporal lobe of the nondominant hemi-
19 sphere is much more important for visual discrimination than the intactness of
20 the dominant hemisphere whose ablation interferes with verbal associability.

21 The investigations by various authors agreed in the conclusion that dis-
22 orders in tactual associations are produced primarily by ablations in the
23 parietal lobe. Ghent et al (Bibl.28) found in such patients that the tactual
24 discrimination of various surface qualities was clearly reduced after parietal
25 ablations. Weinstein et al (Bibl.118), who made a test on the discrimination
26 ability for various degrees of surface roughness, came to the same conclusion.

1 In another report (Bibl.116), the same author mentioned that such patients com-
2 mit more errors in estimating weights placed into their hand. The author was
3 also able to demonstrate that this weight-judgement deficit became noticeable
4 only if one weight was placed in each of the hands of the patient who then had
5 to determine which one was heavier. If the first weight was first placed into
6 one hand and the other weight into the other hand later, it was difficult to
7 differentiate this patient from a control patient. It was typical that a
8 patient with unilateral brain lesion underestimated the weight of the object in
9 the hand which was contralateral to the lesion.

10 These few reports already show that the application of tests similar to
11 those used in animal experiments will yield results comparable to the experi-
12 mental data obtained on konkeys. No equivalent work on a possible localization
13 of the discriminatory ability for other sensory qualities is available in any
14 systematic fashion.

15 Another problem is the question whether an ablation of any brain portion
16 will produce in human subjects a failure of the "instantaneous memory", as /195
17 had been the case in Macacus monkeys who failed in delayed tasks after lesion
18 of the frontal cortex or of the nucleus caudatus. Milner and Penfield (Bibl.61)
19 encountered such a deficit after bilateral deep lesions of the temporal lobe.
20 Scoville and Milner (Bibl.104) discovered that this deficit depends on the
21 depth of penetration of the lesion through the temporal brain area into the
22 hippocampus. Walker (Bibl.114) also found that a lesion of the hippocampus re-
23 sults in such a deficit but, according to him, it is not absolutely necessary
24 that a bilateral ablation of the hippocampus be made. Until now, these find-
25 ings thus contradict the results of animal experiments where a similar deficit
26 was encountered after frontal-brain ablations. No reports on the ablation of

the hippocampus and its effect on the "instantaneous memory" in monkeys are available. In summation, it may be stated with respect to these investigations that an agreement between animal findings and human-subject findings may be obtained whenever an analogous experimental technique is used for both cases. To date, this has been done in very few cases and only some of these studies met the strict control conditions that are readily satisfied in monkey experiments. The literature on the speech center and dominance of one of the two hemispheres will not be discussed in this connection. More recent results of research in this field were compiled by Penfield and Roberts (Bibl.82) in an extensive survey.

Summary

The present report gives a general view over the effects produced by ablations in the secondary cortex of the Macacus monkey on its performance in various learning tests. The most important results of the discussed investigations are compiled in Table 1. This compilation shows that, for the secondary or association cortex of Macacus monkeys, a distinct subdivision into function-specific areas exists, a matter which requires some further investigation in many respects.

The lower lateral and ventral area of the temporal lobe is essential for the visual learning ability. This field is closely connected, from a functional viewpoint, with the primary visual cortex in the occipital lobe whose ablation, in contrast to that of the temporal cortex, results in perceptive function deficits rather than in associative deficits. After ablation of the parietal secondary cortex, monkeys lose the ability to learn tactual discriminations. Until now, it was impossible to define a specific area for the learn-

TABLE 1. SURVEY OVER THE EXPERIMENTALLY FOUND EFFECTS OF BRAIN ABLATIONS ON THE MACACUS MONKEYS

(Compare the Extent of "Standard Ablations" with Fig.2. When no Special Notation is Given, Bilateral Ablations are Involved)

Tested Tasks	Focal Ablations with Behavior Deficit	Control Ablations without Behavior Deficit	Characteristics of the Behavior Deficit
A. Behavior Deficits of Sensory Type			
Visual Discrimination: Learning to select the correct of two or more simultaneously presented visual stimuli	- temporal standard ablation	- only unilateral temporal standard ablation	Learning and relearning are postoperatively possible but only with a greater learning effort. New learning is more influenced by the operation than relearning. The learning of difficult tasks is more impaired than that of easier tasks. A recuperation of the learned function, spontaneously with time, is questionable. The behavior deficit is of "integrative" nature rather than of a perceptive nature.
	- unilateral temporal standard ablation, combined with contralateral occipital dissection of the posterior third of the corpus callosum	- superior temporal cortex dissection of the corpus callosum	
		- parietal standard ablation	
		- occipital standard ablation (produces only negligible learning deficit)	
		- frontal standard ablation	
		- orbital frontal cortex	
		- anterior insular cortex	

Tested Tasks	Focal Ablations with Behavior Deficit	Control Ablations without Behavior Deficit	Characteristics of the Behavior Deficit
Visual Perception: Field of vision, food recognition, size discrimination, visual acuity (recognition of the intersections of crossed strings)	- occipital standard ablation	- periamygdal cortex - posterior hippocampus - Pulvinar - Colliculi superiores - temporal standard ablation (produces only negligible behavior deficit) - frontal standard ablation - frontotemporal cortex (gyrus orbit. post., insular and periamygdal cortex) - temporal standard ablation	"Overtraining" before the operation reduces the post-operative behavior deficit The behavior deficit becomes more distinct the more difficult the "problem" (small differences in size discrimination tests, complex arranged strings). Partially, spontaneous recuperation of the function
Tactual Discrimination: Learning to select the correct one of two simultaneously presented surface qualities	- parietal standard ablation	- frontotemporal cortex (gyrus orbitalis posterior, insular and periamygdal cortex)	

Tested Tasks	Focal Ablations with Behavior Deficit	Control Ablations without Behavior Deficit	Characteristics of the Behavior Deficit
<p>Olfactory Discrimination: Learning to select the correct one of two simultaneously presented odors</p> <p>Gustatory Perception</p>	<p>- lateral, inclusive polar-temporal cortex</p> <p>- frontotemporal cortex (gyrus orbitalis posterior, insular and periamygdal cortex)</p>	<p>- frontal standard ablation</p> <p>- temporal standard ablation?</p> <p>- temporal standard ablation</p>	<p>Slower learning and relearning of tasks after the operation</p> <p>Eating of quinine-containing food</p>
<p>Auditory Discrimination: Depressing of one or the other of two levers, depending on the quality of a presented tone</p>	<p>- ??</p>	<p>- frontal standard ablation</p> <p>- nucleus caudatus</p>	<p>A task very difficult to learn for the Macacus monkey</p>

Tested Tasks	Focal Ablations with Behavior Deficit	Control Ablations without Behavior Deficit	Characteristics of the Behavior Deficit
B. Behavior Deficits of Nonsensory Type			
Delayed Reaction: Two feeding places, three test phases: 1. Signalization of the rewarded feeding place with a posi- tive stimulus and of the empty feeding place with a nega- tive stimulus. 2. Masking the pos- sibility of seeing the situation during the delay. 3. Ani- mal choosing between two neutrally cov- ered feeding places	- region on both sides and in the depth of the sulcus princi- palis within the frontal standard ablation - nucleus caudatus	- cortex of the frontal lobe outside of the region around the sulcus principalis - temporal standard abla- tion - parietal standard abla- tion - occipital standard abla- tion - nucleus dorsomedialis of the thalamus - motor and premotor cortex - premotor optical fields	Learning and relearning are postoperatively impossible. No spontaneous recuperation. Deficit independent of the length of the delay in the test. In addition to the classical problem complex, the following must be learned postoperatively: a) correct reaction or non-reaction to only one stimulus after delay; b) if, in the case of two stim- uli, the animal is allowed to see both selection spots dur- ing the delay (pseudodelay)

Tested Tasks	Focal Ablations with Behavior Deficit	Control Ablations without Behavior Deficit	Characteristics of the Behavior Deficit
Hyperactivity	<ul style="list-style-type: none"> - ablation in various regions of the frontal cortex - Nucleus caudatus 	<ul style="list-style-type: none"> - temporal standard ablation - parietal standard ablation - occipital standard ablation 	Partially spontaneous recuperation after operation. Typical circling of cage

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C. "Sensory" Behavior Deficits of Nonspecific Type

Successive Discrimination: Presentation of an individual stimulus (auditory, visual). The quality of the stimulus indicates whether the feeding place underneath the individual stimulus is empty or full	<ul style="list-style-type: none"> - dorsolateral frontal cortex - nucleus caudatus - temporal standard ablation for visual tests 	<ul style="list-style-type: none"> - ?? - temporal standard ablation for auditory tests 	<p>Behavior deficit is greater in auditory than in visual tasks.</p> <p>Delayed learning of the negative stimulus significance (= inhibition deficit?)</p>
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Tested Tasks	Focal Ablations with Behavior Deficit	Control Ablations without Behavior Deficit	Characteristics of the Behavior Deficit
Retraining: Switching from positive to negative stimulus significance in simultaneous serial selection tests	- dorsolateral frontal cortex	- temporal standard ablation	Perseveration of the frontal-operated animals for positive signal significance
Weak Punishment Motivation: Weak electroshock punishment in auditory test. Minor physical effort in tactical discrimination	- dorsolateral frontal cortex	- ??	Postoperatively, only normal learning if punishment or physical effort for opening the feedbox is too great (= loss of inhibition)
Fusion Frequency of Optical Light Flashes	- temporal standard ablation - occipital standard ablation (decrement in fusion frequency)	- frontal standard ablation (increase in fusion frequency)	

ing of auditory discriminations, outside of the primary auditory cortex. An area for the learning of olfactory discrimination is located in the temporal /199 lobe, but no more accurate localization, specifically a delimitation toward the visual associative area, is known at present. No conclusive studies are in existence on the localization of a field for gustatory discriminations.

A total ablation of the frontal secondary cortex results in an irreparable failure of the ability for delayed reactions. The psychological significance of this ablation is not yet clear. In any case, it is not merely a question of a simple memory loss. In addition to this deficit, frontal ablations result also in failures of manifold types whose interpretation is not completely certain on the basis of available data. Thus, the ability to learn sensory discriminations is lost for various modalities, but only if the corresponding test had been conducted in a certain manner. Such failures, consequently, are not of a sensory-specific type as was the case for ablations in the posterior secondary cortex (parietal, temporal, and occipital secondary cortex). Other consequences of frontal ablations are a typical hyperactivity and, in many cases, a disturbance of the normal emotional behavior.

The correlation of the above findings with human pathology is quite obscure at present, which is most likely due to the fact that only in a few cases has the same systematics of the experimental technique been used for human subjects.

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